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Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: February 1, 2015 to April 30, 2015

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft". The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure) significant aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

2. Activities this period

During the period of this report, the implementation of Actuator Disk Model with 1D Gaussian distribution to GENHEL-PSU helicopter simulation code has been completed. Initial tests have been performed to determine the optimal values of Gaussian shape function parameters. Fully coupled simulations of the helicopter hovering in an open domain were performed using loose coupling approaches with the actuator disk model.

Implementation of the 1D Gaussian distribution with Actuator Disk Model

Implementation of the Actuator Disk Model (Figure 1) with the coupled GENHEL-PSU / CRUNCH simulation code was explained in the previous reports. The initial simulation results showed that implementation of a distribution function could be used to smooth the actuator point forces out over the surrounding grid cells to obtain a more accurate and numerically stable prediction of rotor induced velocities.

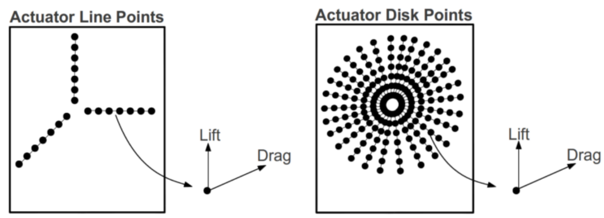

Figure 1 - A schematic of Actuator Line Model (ALM) and Actuator Disk Model (ADM)(Taken from Ref. 1).

GENHEL-PSU calculates the local flow velocities and the body forces on each rotor blade segment. The lift and drag per spanwise length are calculated based on the local wind speed and angle of attack,

$$(\mathbf{L}, \mathbf{D}) = \frac{1}{2}\rho {V_{rel}}^2 c(C_L \mathbf{e_L}, C_D \mathbf{e_D}),$$

where α is the local angle of attack respect to the chord, $C_L(\alpha)$ and $C_D(\alpha)$ are the lift and drag coefficients, respectively, ρ is the density, V_{rel} is the local velocity magnitude, c is the chord and e_L and e_D are the unit vector in the direction of the lift and drag. The force per spanwise unit length is written as the vector sum $\mathbf{F} = \mathbf{L} + \mathbf{D}$.

The actuator disk model approach needs the forces at each blade element to be scaled by a solidity factor,

$$\sigma = \frac{NA_B}{A_r} \quad \text{or} \quad \sigma = \frac{N}{\psi_n},$$

where N is the number of blades, A_B is the area of an individual blade section, A_r is the swept area of the blades and ψ_n is the number of actuator lines around the azimuth used to generate the actuator disk.

The applied force normalized by the solidity factor becomes,

$$\mathbf{f} = \mathbf{F}\sigma.$$

A 1D Gaussian distribution, as suggested by Mikkelsen (Ref. 6), can be used to smooth the actuator point forces out over the grid cells at planes vertically stacked in the normal direction of the rotor disk plane. By taking the convolution of the force with a regularization kernel,

$$\mathbf{f_\epsilon} = \mathbf{f} \otimes \eta_\epsilon^{1D}, \quad \eta_\epsilon^{1D}(p) = \frac{1}{\epsilon\sqrt{\pi}} \exp\left[-\left(\frac{p}{\epsilon}\right)^2\right],$$

where p is the distance between the rotor disk plane and the planes vertically stacked in the normal direction of the rotor disc and ϵ decides the Gaussian width where the forces distributed from its initial point (Ref. 7).

Simulation Results

Simulation results were performed using fully coupled solutions of the rotorcraft flight dynamics and CFD flow field. First, a Gaussian sensitivity test was performed to determine the Gaussian distribution factor with a suitable choice of grid resolution. In these tests, the rotorcraft was frozen in place, such that the fuselage flight dynamics were not solved, but the rotor blade dynamics were integrated. Next, free flight simulations with the NLDI controller were performed. Simulations of the helicopter hovering were

performed in an open domain in both IGE and OGE conditions are presented. All calculations were performed using parallel computing with 128 CPUs on the COCOA4 cluster at Penn State.

Case I: Gaussian Sensitivity Tests

A Gaussian distribution function is commonly used with the Actuator Disk Model (ADM) approach. It was studied by several researchers (Ref 1, 3, 4, 5, 6, 8) and it was shown that thrust and power values approximated by ADM/ALM with Gaussian distribution are dependent on three parameters; ϵ, Δ_{grid} and Δ_b which are the Gaussian width parameter, the grid resolution and the width of the discrete blade section, respectively (Ref. 8). Martinez (Ref. 1) showed that the number of blade sections needs to be high enough in order to have a smooth distribution of forces through the blade and a value smaller than $\Delta b/\Delta_{grid}= 0.75$ was suggested. He suggested that the ϵ value should be greater than $2\Delta_{grid}$ in order to avoid numerical instabilities in the solver. While these guidelines were suggested for a 3D Gaussian distribution, we apply them to a 1D Gaussian distribution. A grid formation with $\Delta b/\Delta z = 0.75$ is generated in the direction normal to the rotor disk to locate the vertically stacked planes. It was decided to perform a Gaussian sensitivity test for the Gaussian distribution factor ϵ with 10 planes located above and below the rotor disk.

The projected force decays to its 0.1% of its original value at

$$p_{max} = \epsilon.\sqrt{\log(1000)} \approx 2.63\epsilon$$

where p_{max} is the maximum distance between the rotor plane and the plane where actuator point forces are distributed. The ratio of p_{max}/ϵ is an important parameter. A ratio of p_{max}/ϵ smaller than 2.63 will lead to a difference between the actual point force and the total projected body force which is not desired.

In order to avoid coarse discretization above and below the rotor disk plane, 10 planes were vertically stacked above and below the rotor plane in 0.5ft increments, resulting in p_{max}=5ft. While holding the grid resolution ($\Delta_{grid}= 0.5ft$) and blade section width ($\Delta_b= 0.35ft$) constant, a sensitivity test was performed for different values of the Gaussian width parameter.

Figure 2 shows the distribution of the actuator point force, at 0.75 radius of the rotor blade and at a random time of the simulation, projected onto the vertically stacked planes for different values of ϵ. It can be seen that, the higher values of ϵ spreads the actuator point forces out onto the vertically stacked planes and decreases the force jumps across the planes. However, using a value of ϵ higher than 10 starts to decrease the 2.63 ratio and increases the difference between the actual point force and the projected body force. **Figure 3** shows the thrust values calculated by GENHEL-PSU with the vehicle dynamics frozen using the CFD induced velocity approximation for the different values of ϵ and the Pitt-Peters inflow model. It can be seen that for the higher values of ϵ, thrust values calculated by GENHEL-PSU using CFD data produces results similar to the Pitt-Peters inflow model. There is still a significant difference (14%), but it should be noted that the 3 state Pitt-Peters inflow model is not necessarily particularly accurate for predicting hover performance. Ultimately $\epsilon = 10\Delta_{grid}$ was chosen. **Figure 4** shows the projection of the non-dimensional radial distribution of the lift force of a blade spread onto vertically stacked planes, 5 ft. above and below the rotor disk plane, when $\epsilon = 10\Delta_{grid}$; $\Delta_{grid}= 0.5ft; \Delta_b= 0.35$ is used. Beyond this point, all the simulations are performed using these Gaussian parameters.

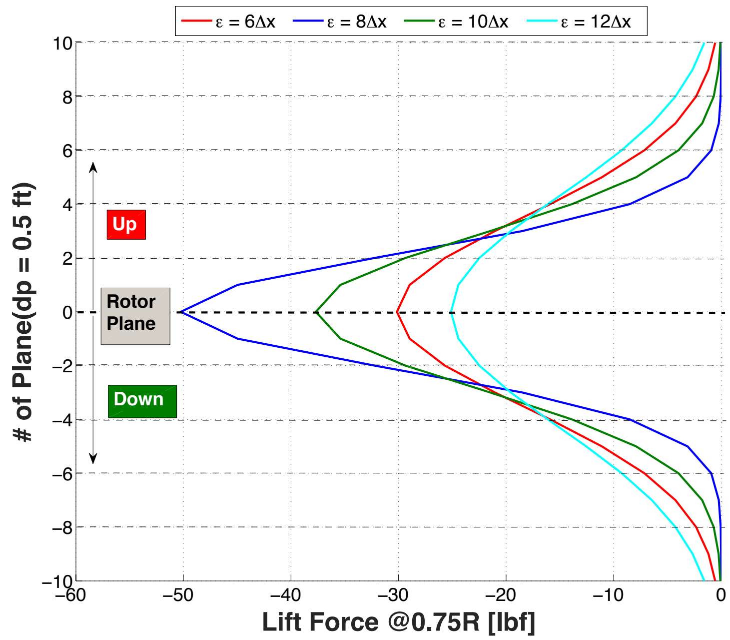

Figure 2 - Distribution of actuator point forces at 0.75R on vertically stacked planes for different values of ϵ.

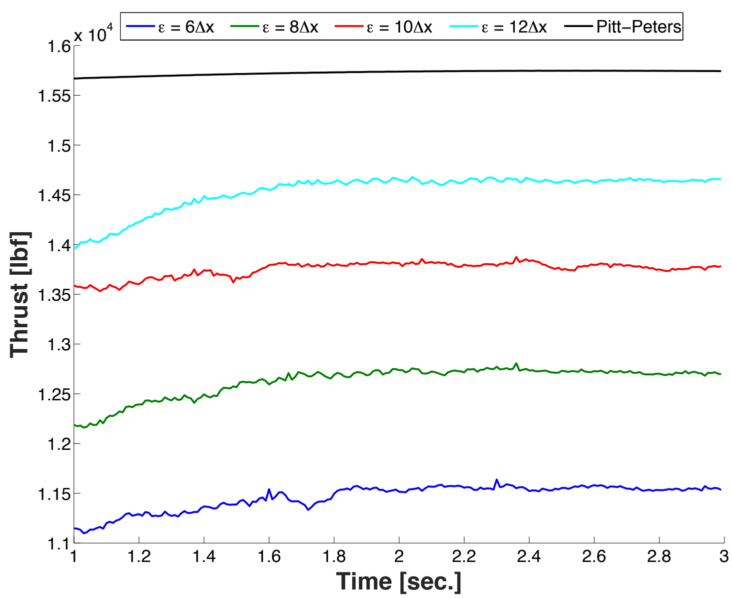

Figure 3 - Thrust values calculated using coupled simulations (fuselage frozen) with different values of ϵ.

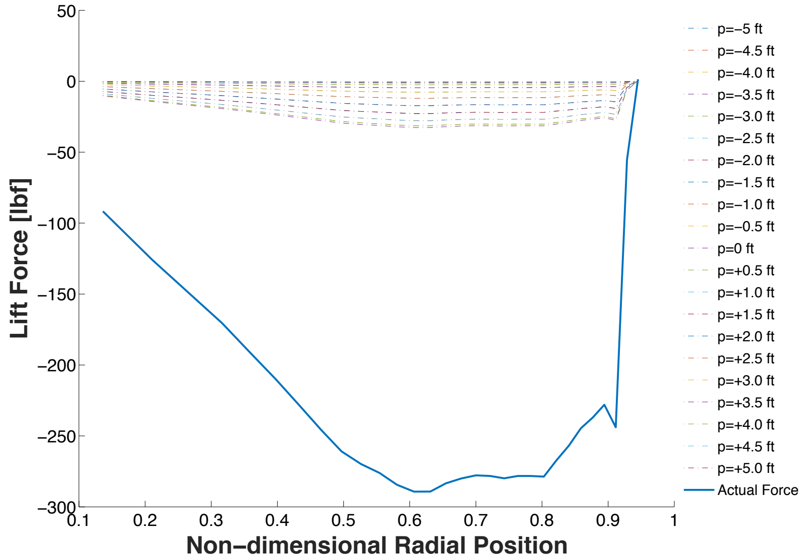

Figure 4 - The projection of the non-dimensional radial distribution of the lift force onto vertically stacked planes, 5 ft. above and below the rotor disk plane, with $\epsilon = 10\Delta_{grid}$, $\Delta_{grid} = 0.5ft$, $\Delta_b = 0.35$. Lift is positive down in this analysis.

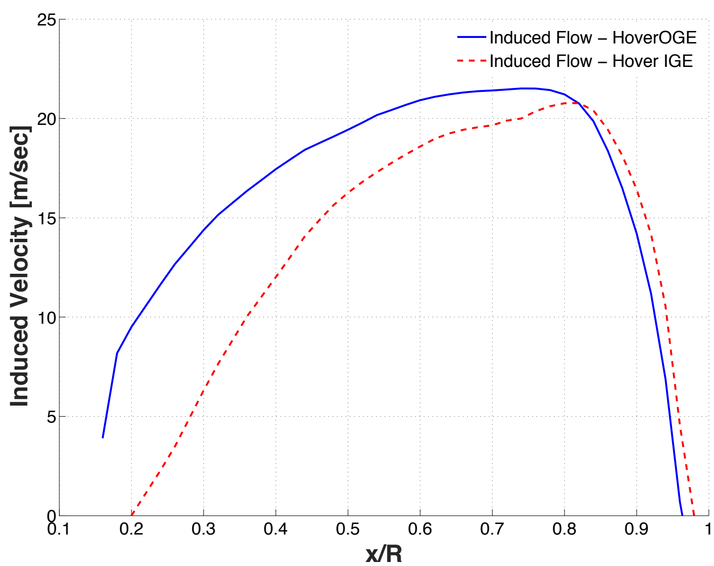

Figure 5 - Time averaged induced downwash velocity distribution on advancing rotor blade for fully coupled CFD.

Case II : Hover in an Open Domain

In these simulations, the utility helicopter hovers in an open domain both in and out of ground effect. Simulations have been performed with the existing GENHEL-PSU inflow model and with CFD coupling. The fully coupled simulations start in freeze-mode, in which the helicopter body is held at a specific position in the air and the rotor blades move freely. At the beginning of the simulation, GENHEL-PSU uses a Pitt-Peters finite state inflow model to trim and sends the blade positions and aero loads to the flow solver as initial values. After initialization, GENHEL-PSU starts to use the CFD-predicted induced velocities to calculate the blade loads, but the helicopter stays in freeze mode. This buffer phase helps the CFD solver to develop the rotor downwash and prevents potential CFD convergence problems. After the 5th second of the simulation, GENHEL-PSU enters free fly-mode. In this mode, both the helicopter and the rotor disk move freely while GENHEL-PSU and the CRUNCH CFD® solver are fully coupled to each other. The controller helps to regulate the aircraft and it reaches a new hover trim condition.

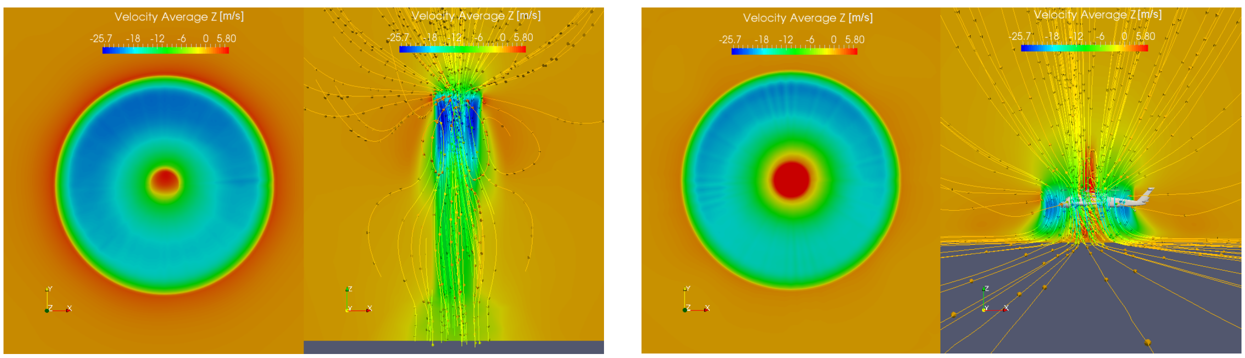

Figure 6 - Distribution of vertical velocity on rotor disk plane and the downwash plane, helicopter hovers OGE and IGE, respectively.

Figure 6 shows the distribution of velocity magnitude on rotor disk and downwash planes, when the helicopter hovers at OGE and IGE conditions, respectively. The impact of rotor downwash can be easily seen from the contour plots. The average predicted rotor downwash velocity is about 15 m/s (**Figure 5**), which is slightly higher than what is predicted by the 3-state Pitt-Peters inflow model (~12 m/s). The average downwash predicted by the Pitt-Peters inflow is essentially equivalent to idealized momentum theory, and is expected to be slightly low.

Figure 7 to **Figure 9** show the time history of the response in position, attitude and control inputs of the closed loop helicopter for OGE hover without CFD, and the fully coupled simulations of hover IGE and OGE. For the coupled cases, there is a transient in the response of the helicopter as it enters free flight. The NLDI controller must then re-trim the helicopter, which it successfully does within several seconds, while the helicopter only drifts a few feet from the original hover location.

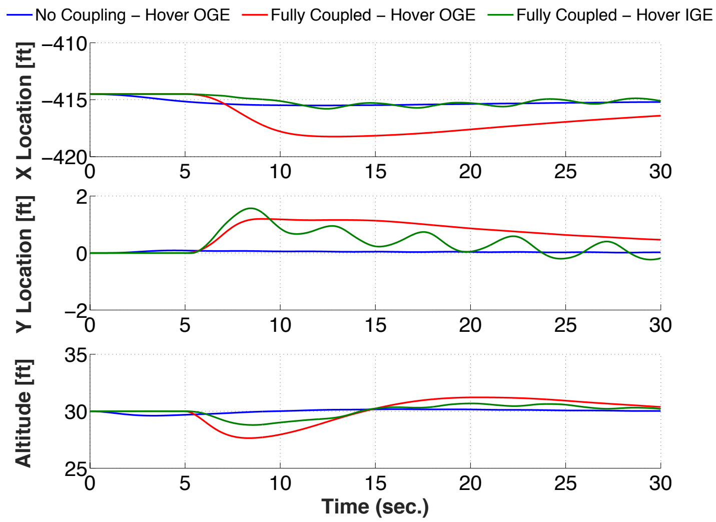

Figure 7 - Variations in position of the simulated helicopter in hover OGE and IGE.

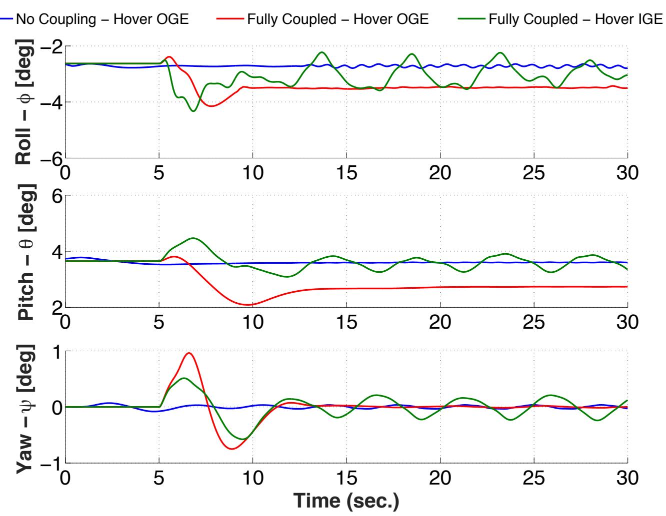

Figure 8 - Attitude response of the simulated helicopter in hover OGE and IGE.

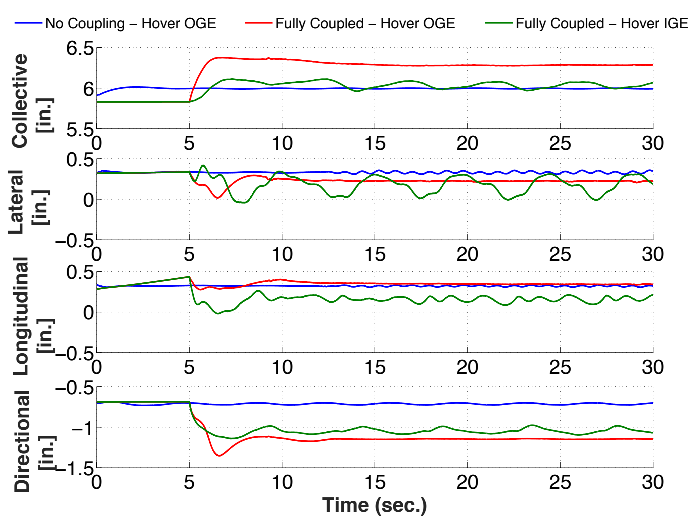

Figure 9 - Control responses of the simulated helicopter in hover OGE and IGE.

The coupled results also show a dynamic behavior for the In Ground Effect (IGE) condition. As can be seen from **Figure 8**, there are fluctuations in the attitude response of the helicopter with a period of approximately 5 seconds. The oscillations result in a small amount of "wobbling" in the aircraft position as well as control responses in reaction to the disturbances. The impact of the fluctuation is much more active in the roll dynamics of the helicopter (possibly because this axis has the lowest inertia). Experimental studies have shown a significant perturbation to the flow near the rotor blades is caused when the wake of a helicopter rotor interacts with the ground (Ref. 9). Minor oscillations when hovering in ground effect have also been observed by pilots. If these solutions are accurately predicting this phenomenon, it shows the potential of using coupled simulations to analyze ground interaction effects. Especially during the transitional flight, the interaction between the main rotor flow and the ground vortex can have a crucial effect on handling qualities. Curtis (Ref. 10) defined two distinct flow regimes (**Figure 10**) when the rotorcraft wake interacts with the ground during low speed flight:

1. Recirculation of the wake ahead the rotor at very low advance ratios, causing additional inflow through the forward part of the rotor. (Ref. 10) (Recirculation Regime)

2. Formation of a horseshoe ground vortex under the rotor at higher advance ratios with its associated interactions. (Ref. 10) (Ground Vortex Regime)

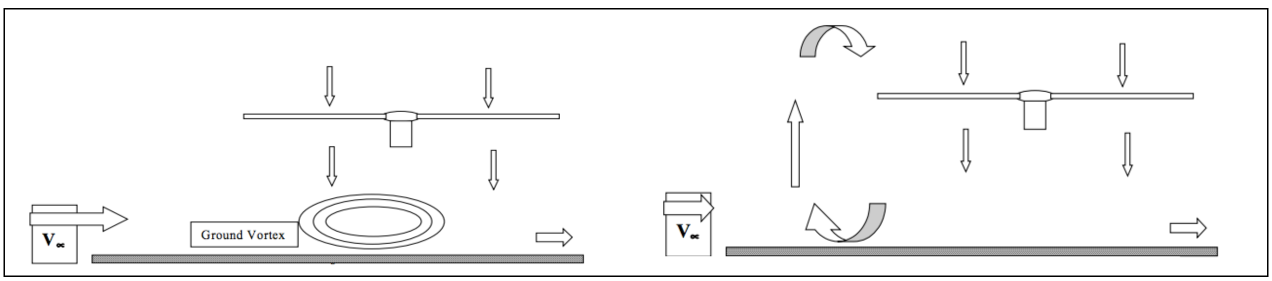

Figure 10 – Schematic of Ground Vortex (left) and Recirculation zone(right), taken from Ref 9

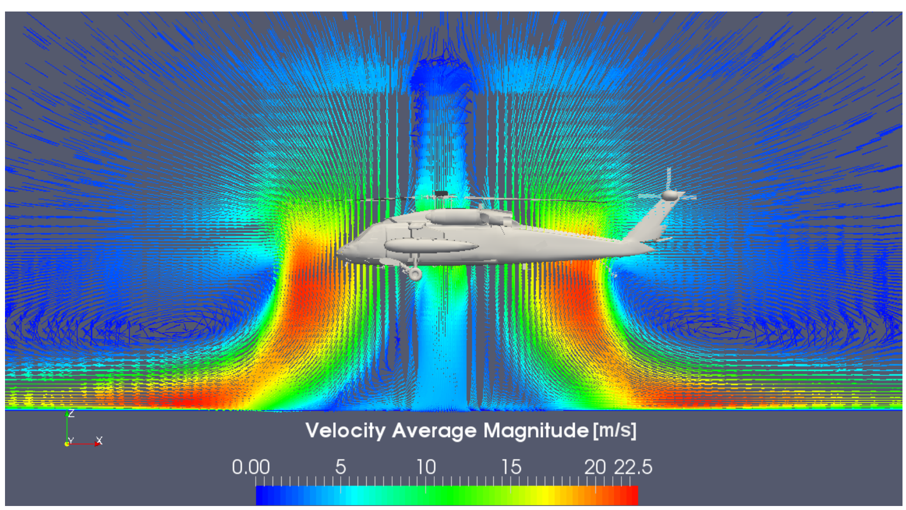

Figure 11 - Flow vector field distribution of the helicopter in hover IGE, 25 ft (approximately 1R) above the ground.

Figure 11 shows the flow vector field distribution of the helicopter hovering IGE. Two recirculation flow regimes can be observed from the figure: 1) the larger outflow induced recirculation region, outside of the rotor tips and 2) the smaller recirculation regions under the rotor disk. The fluctuations observed in the coupled simulation might be associated with the recirculation flow regime cited by Curtis (Ref. 10). Validation data is required to fully understand if this is an accurate model of this phenomenon. In future studies, we will also investigate the flight dynamics behavior of the helicopter in IGE condition during low forward flight speeds.

In addition to the hover results, a number of additional simulations were also performed for ship approaches and hover over the ship deck. These are not shown here for brevity. These results are presented in the AHS Forum paper, and will be discussed further in future progress reports.

3. Significance of Results

The results show the successful implementation of Actuator Disk Model with 1D Gaussian distribution to the GENHEL-PSU. The results will provide more accurate predicted thrust values compared to the ADM and ALM implementations w/o Gaussian distribution, which were implemented on the previous reports. Fully coupled simulation results show the successful downwash development and relatively correct induced velocities. Hover IGE simulation results shows a physical phenomena of rotor downwash/ ground interaction.

4. Plans and upcoming events for next reporting period

- Continue development of fully coupled simulations: Implementation of 3D Gaussian shape function to distribute the source terms spanwise could be helpful to obtain more accurate predicted induced velocity values.
- We will look at some more forward flight and ship cases.
- Communication interface will be optimized for faster simulation process. We are currently using file IO. We are looking at other communication protocols including named pipes.
- We will investigate the flight dynamics behavior of the helicopter in IGE condition during forward flight speeds.
- We have a meeting planned with NAVAIR in late May 2015.
- We are preparing a draft paper for AIAA SciTech 2016.

5. References

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6. Transitions/Impact

No major transition activities during the reporting period (other than the submission of the AHS paper described below).

7. Collaborations

Penn State has collaborated with CRAFT Tech and conducted regular discussion with them.

8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

9. Publications

The paper “Coupled Flight Dynamics and CFD Simulations of the Helicopter / Ship Dynamic Interface” will be presented at AHS Forum 71 in the Simulation & Modeling session on May 7, 2015 at Virginia Beach, VA. The final paper has already been submitted and will be published in the proceedings.

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